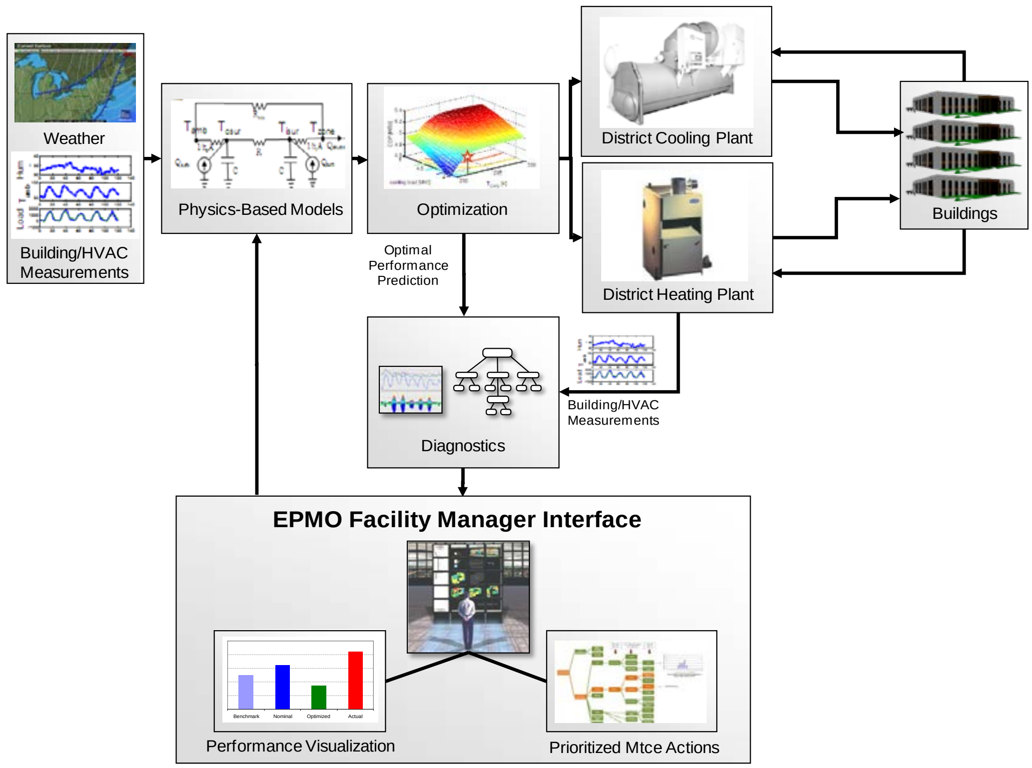
ESTCP
Cost and Performance Report

(EW-201142)



Energy Performance Monitoring and Optimization System for DoD Campuses

February 2014

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ACRONYMS AND ABBREVIATIONS

AHU	air handling unit
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BACnet	Building Automation and Control Network
BLCC	Building Life Cycle Cost
BLOM	Berkeley Library for Optimization Modeling
BMS	building management system
BTU	British thermal unit
CFM	cubic feet per minute
CO_2	carbon dioxide
COTS	commercial off-the-shelf
DDC	direct digital control
DoD	U.S. Department of Defense
DRF	Drafting Technology
EMCS	Energy Management and Control System
EPMO	Energy Performance and Monitoring Optimization
ESTCP	Environmental Security Technology Certification Program
FDD	Fault Detection and Diagnosis
gpm	gallons per minute
HVAC	heating, ventilation and air conditioning
IPOPT	Interior Point Optimizer
ISO	International Standards Organization
kWh	kilowatt hour
LEED	Leadership in Energy and Environmental Design™
MPC	Model Predictive Control
NIST	National Institute of Standards and Technology
NPV	net present value
OSD	Office of the Secretary of Defense
OUSD	Office of the Under Secretary of Defense
ROM	reduced order model

ACRONYMS AND ABBREVIATIONS (continued)

SIR	savings to investment ratio
SQL	Structured Query Language
TRL	Technology Readiness Level 6
UTRC	United Technologies Research Center
VAV	variable air volume

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EXECUTIVE SUMMARY

The United Technologies Research Center (UTRC), with sponsorship from the U.S. Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) for Energy and Water, conducted a demonstration of the Energy Performance and Monitoring Optimization (EPMO) system prototype used to improve the energy efficiency of both heating and cooling systems. The EPMO system was implemented in this demonstration project as an extension of the existing Building Management Systems (BMS) for optimization of control schedules, energy performance visualization and system diagnostics for building and district heating systems. The system was demonstrated in two buildings at Navy Recruit Training Center in Great Lakes, Illinois, during the 2012-2013 heating season for three air handling units (AHU) and 54 terminal units.

The EPMO system integrates optimal control algorithms with system performance monitoring, diagnostic and visualization tools. The control algorithms use weather forecast data, zone sensor data, meter data and information from the AHUs and terminal units to generate optimal control schedules. For example, an optimal control schedule can control the discharge air temperature values to minimize energy consumption while meeting comfort constraints. The EPMO diagnostics tool uses the sensor and meter data to detect and isolate equipment faults, such as stuck dampers or valves, to prioritize the fault correction based on energy impact. The EPMO visualization tool continuously displays the diagnostics information to facilitate understanding the equipment fault impacts on energy consumption.

The main technical objectives of the demonstration for energy savings and system robustness were met. Based on the performance data recorded during the demonstration period, it was estimated that, on average, the EPMO system exceeded the energy consumption reduction target of 20% and improved occupant thermal comfort by reducing the number of instances outside of the temperature comfort band by 75%. The scalability of the EPMO system was confirmed through the use of an automated method for control schedule optimization, which requires minimal customization for each new system compared to the effort required to retune baseline system control schedules. The robustness of the EPMO system was confirmed by the system correctly diagnosing equipment faults for heat exchanger dampers and valves 84% of the time.

The economic objectives of the demonstration were also met with a Simple Payback of 3.5 years and Savings-to-Investment Ratio of two for the EPMO system for the demonstration site buildings. The EPMO system performance was estimated using the sensor and meter data recorded during 26 demonstrations days conducted during the period of November 2012 to March 2013 for three AHUs and 54 terminal units. These economic impacts depend on several variables (equipment age, building type, etc.) and may be different for other sites. A unique feature of the EPMO system is its adaptability that can lead to reduced operational costs by automatically re-optimizing the control schedules to accommodate equipment faults that are detected in real-time.

The scalability and energy savings potential demonstrated in this effort proved to be a successful demonstration that has led to continued efforts and investments from UTRC targeted at maturing the EPMO system components, including automation to operate without expert supervision.

Encouraged by the results and potential of advanced diagnostics and controls technologies implementation in the building heating, ventilation and air conditioning (HVAC) application space, UTRC in cooperation with UTC Climate, Controls, and Security business unit is continuing the development and maturation of these technologies with the objective of commercializing them in the near future. The EPMO diagnostics technology has continued to be matured on several full-scale building HVAC systems. The EPMO optimal control system technology was further matured and implemented in the Energy Efficient Buildings Hub, in Philadelphia, Pennsylvania. In addition, UTRC has also been developing and demonstrating adaptive optimization-based building HVAC control algorithm with the objective of maximizing energy savings and comfort control with less reliance on a-priori developed building and HVAC equipment models.

1.0 INTRODUCTION

1.1 BACKGROUND

The Department of Defense (DoD) is the largest single user of energy in the United States (U.S.), representing 0.8% of the total U.S. energy consumed and 78% of the energy consumed by the Federal government (Office of the Under Secretary of Defense [OUSD], 2008).. Approximately 25% of the DoD energy use is consumed by its buildings and facilities. The DoD currently has 316,238 buildings across 5,429 sites and in 2006 its facility energy bill was over $3.5 Billion (DoD, 2008a). The Office of the Secretary of Defense (OSD) published an energy policy to 'ensure that the DoD infrastructure is secure, safe, reliable and efficient' (DoD, 2008b), and subsequent energy policy is being guided by the Energy Policy Act of 2005, Executive Order 13423, and the Energy Independence and Security Act of 2007 to ensure a 30% energy reduction by 2015. Due to the large energy footprint of DoD facilities, increasing building energy efficiency offers the largest opportunity for reducing DoD energy consumption. Building heating, ventilation and air conditioning (HVAC) systems consume greater than 30% of a building's energy consumption[1] and ensuring sustained, operational efficiencies of building HVAC systems is the focus of this proposal.

Buildings are subject to significant uncertainties and changes during their lifecycle, including weather cycles, changes in facility usage and occupancy, and equipment (including actuators and sensors) degradation. Consequently, building systems, equipment and controls optimized, designed, and configured initially cannot be expected to maintain optimal energy performance during the course of the facility operation, which spans several years or even decades. In the case of district heating system that serve a campus of buildings, the hot water flow rates and temperatures are configured to be either fixed or selected based on local feedback measurements at an individual building (e.g., outside air temperature). The actual loads seen by the district heating system that reflect the variation across the campus building loads, uncertainty in environmental conditions and operational states (normal or faulty) are not utilized to optimize operation schedules for energy performance.

It is now well recognized that while typical retrofit measures involving the upgrade, modification or tuning of heating and cooling plants systems and their controls can provide 10-20% reduction in energy consumption, the benefits quickly erode due to changes in the facility use or seasonal adjustments[2], thus requiring frequent re-commissioning. Furthermore, there can be discrepancies between the building control sequences actually implemented and those that were intended during design. An ongoing study being performed with ESTCP support in a Leadership in Energy and Environmental Design™ (LEED) Gold DoD facility (EW-200929) revealed significantly higher outside air intake into the air handling units (50% of total supply air flow in comparison to the 30% intended during design stage) resulting from improperly configured outside air damper and improper fan speed tracking. The heating season energy consumption impact of such operational faults was estimated to be nearly 40%. While the individual components and sensors were all operating correctly, the faulty operation and its energy

[1]Energy savings are based on 3.8 billion kilowatt hours (kWh) per year of electricity consumed by DoD facilities in 2006 [1].
[2] Piette/Mills/LBNL Study on Performance Degradation & Commissioning

performance impact was not visible to the operator using a state-of-the-art building automation system.

The demonstration of an optimally configured building control system with integrated real-time performance monitoring and diagnostics at the scale of a campus of buildings was proposed for this effort. Such an energy performance monitoring and optimization (EPMO) system can ensure the sustained operation of facility energy conservation measures across a broader stock, and also deliver a platform where new opportunities for energy performance improvements can be identified and justified on an ongoing basis. The key technical challenges in accomplishing repeatable and robust solutions to the above problem with economically attractive payback are:

1. Obtaining models of the heating plant, buildings and control systems that can be assembled rapidly and deployed easily in commercially available building management system (BMS) platforms;
2. Achieving energy consumption reduction through advanced controls when the loads and demand are highly uncertain and actuators are constrained; and
3. Having techniques for energy performance visualization and diagnostics to automatically detect and isolate faults that are responsible for system-level performance degradation.

The United Technologies Research Center (UTRC), in partnership with the University of California, Berkeley and Naval Station Great Lakes demonstrated a campus-scale EPMO system prototype that utilizes advanced algorithms for real-time optimization of control schedules and analytical tools for energy performance visualization and diagnostics. The demonstration focused on a district heating system connected to buildings 7113 and 7114 at the Naval Station campus.

Expected Benefits: It is expected that the broad deployment of an EPMO system for district heating[3] systems at DoD facilities will deliver and sustain 20% energy savings achieving greater than 0.75 billion kWh per year or $75M per year[4] with a tangible reduction of 450,000 metric ton of carbon dioxide (CO_2) per year[5]. The energy reduction is achieved by providing HVAC set points that would optimize system level performance and applying energy performance monitoring and diagnostics that enable facility engineers to more proactively identify and correct poor system performance. For the selected demonstration site, the demonstrated simple payback is less than 5 years.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of this project was to develop a standalone software environment for demonstrating a multi-building campus EPMO system for district heating system that can achieve 20% energy savings. The demonstration was carried out at the Naval Station Great

[3] It is expected that the EPMO system can reduce energy consumption for cooling system. The level of energy savings has to be evaluated through similar demonstrations.
[4] Energy savings are based on: 1) 0.06 quads BTU chilled water sent out from district cooling systems in the DoD facility; 2) 1 kW/ton efficiency for chilled water plant; 3) Average 10 cents per kWh.
[5] CO_2 emission reduction based on U.S. average of 1329 lb of CO_2/MWh of electricity generated (0.60 metric ton CO_2/MWh). http://www.epa.gov/cleanenergy/energy-resources/refs.html.

Lakes in Illinois for the Bachelor Enlisted Quarters campus buildings 7113 and 7114. The demonstration activities were redirected from the chiller plant that serves the two buildings, as originally planned, to the heating plant, as a result of a mitigation plan generated after one chiller started to malfunction at the beginning of the 2012 cooling season. The EPMO system can be implemented for both chiller and heating plants.

The campus EPMO system, illustrated in Figure 1, consists of integrated technologies for dynamic central plant, building and HVAC modeling, model-based optimal predictive control, and energy performance visualization and diagnostics. The EPMO system was implemented as a software environment that extends the capabilities of the current existing BMS. For the Naval Station Great Lakes demonstration, this system interfaced directly with the Siemens BMS and resided on an independent computer.

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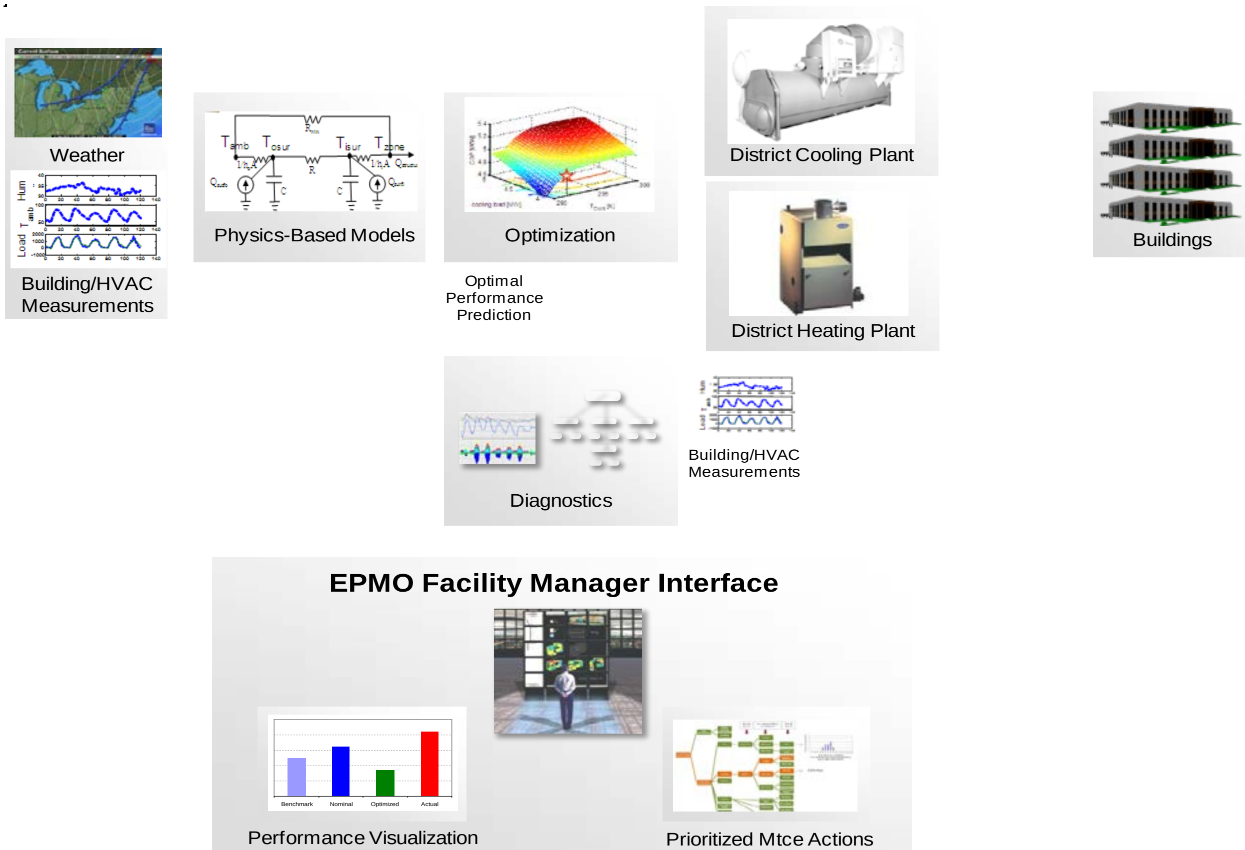

Figure 1. Campus EPMO system.

1.3 REGULATORY DRIVERS

Executive Order 13423 (http://www.whitehouse.gov/news/releases/2007/01/20070124-2.html) and the Energy Independence and Security Act of 2007 (Title IV Subtitle C) require that U.S. federal agencies improve energy efficiency and reduce greenhouse gas emissions by 30% by 2015, relative to a 2003 baseline.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

The campus-scale EPMO system was implemented as a stand-alone software environment, comprising of control and diagnostic algorithms and performance visualization tools that were interfaced directly with the Naval Station Great Lakes BMS for buildings 7113 and 7114. The novelty of the proposed effort consisted of the delivery of a single platform and operator environment that integrates optimal control algorithms that use real-time data and predictive physics-based models with performance monitoring and diagnostic tools that measure actual heating plant and building energy performance.

1) **Control-Oriented Building-System Performance and Zone-Temperature Models.** Dynamic thermal simulation demonstrates how the two buildings interact with the internal and external disturbances. Reduced-order models for HVAC systems and buildings are based on thermodynamics, thermo-fluid law, and heat transfer analysis and are the main tools for generating predictions, diagnostics and control inputs for optimizing the plant operation and building energy utilization performance. Each of the enumerated models was calibrated and validated using measurement data from functional tests and the BMS database. Specific tests were designed for each component by controlling in a coordinated way combinations of actuators (dampers, valves) and set points (flows, discharge temperatures) for AHU and variable air volumes (VAV). The generated functional test data was combined with historical data and used to estimate performance parameters for the models. A segment of the data was used for estimation, and a different segment was used to validate the models, and thus to ensure that the models have adequate predictive capabilities.

2) **Model-Based Optimal Predictive Control.** A module was developed to generate real-time optimal set points for the site building HVAC systems using algorithms that search for the most energy efficient sequences subject to system constraints (building comfort, component performance) and disturbances (weather) by using the control-oriented building-system performance and zone-temperature models. The proposed model-based optimal control formulation integrated in the same framework: HVAC system performance models, zone temperature dynamic models, operational and thermal comfort constraints, and plant efficiency in the same framework (Borrelli and Keviczky, 2008; Borrelli, Pekar, Stewart, 2010; Borrelli, 2003; Baotic et. Al, 2008). In this framework, 4-hour horizon forecasted loads and ambient conditions are used to compute the next set points values that meet the overall system objectives and individual component constraints. The process repeats at 15 minute time intervals and consists of calculating the performance impact of set points and of their efficient selection until an optimal set is reached. This repeated calculation of optimal set points ensures solution robustness and its optimal features by using the most recent measurements, load and ambient forecasts.

3) **Model Library and Language for Optimization Problem Formulation.** A software package that automates the formulation of the Model Predictive Control (MPC) problem for building HVAC systems was developed and employed as part of the project. This tool considerably reduces the effort needed to design the MPC algorithm,

therefore reducing the payback time, and enhances the scalability of the approach. Specifically, the optimization modeling language uses the models described above in conjunction with information such as: thermal comfort constraints, equipment constraints, and energy performance objectives. All the information is automatically integrated into an overall optimization problem that is exported to a solver (Interior Point Optimizer [IPOPT] was selected for this project). Simple modifications were made to each AHU model and the Berkeley Library for Optimization Modeling (BLOM) tool was used to rapidly generate all the problem formulations.

4) **Diagnostics.** The diagnostics module was developed and implemented to: 1) identify and isolate faulty components or ill-configured control schedules that are responsible for the system performance deviation and degradation; and 2) make visible and prioritize the maintenance or facility operation tuning needs by quantifying the energy performance and economic losses occurring. A data-driven based diagnostics approach was used to monitor HVAC system performance. The data was represented in a hierarchical structure of energy usage and individual subsystem delivered functions. Data that was made available within the EPMO system for the building HVAC systems included: 1) BMS operational data (hot water temperatures, hot water flow rate, heating plant pump speed, and AHU fan speed, etc.); 2) HVAC equipment energy usage (AHU, and VAV); 3) weather forecast (outside air temperature and humidity); and 4) estimated and derived parameters (internal loads, unmeasured temperatures etc.) from physics-based models described above. The diagnostic algorithms were implemented and executed during multiple time periods when actuator faults were injected by overriding the controller values, without communicating the override values to the algorithm. Faults at VAV and AHU level were injected, but it was it was determined based on measurements that the AHU faults had a significantly larger energy impact and the effort focused on these faults, in particular on damper and heating coil valve faults (stuck at various positions).

5) **Fault-Accommodating Control.** Model Predictive Control and Diagnostics algorithms have been integrated to generate a fault-accommodating feature of the EPMO system. The optimal control algorithm adapts on-line to the faulty system by using new constraints values when they are detected by the Fault Detection and Diagnosis (FDD) algorithm. Two demonstrations have been conducted where faults have been injected by overriding the BMS commands for AHU dampers and heating coil valve without communicating these overrides to the EPMO system. The FDD algorithm detects the faults, diagnoses them, and communicates the new, stuck actuator positions to the control algorithm. The control algorithm uses the new constrained ranges of the actuators and accommodates to these faults by generating the optimal set points within the new constraints.

6) **Data Management Software.** A software tool chain was customized to allow seamless communication of Control and Diagnostics algorithms with the site basic energy services. The data management software comprises of a set of drivers and incorporates a database where historical BMS data was recorded for allowing both off-line and on-line access. The Control and Diagnostics algorithm receive sensor data from the BMS and communicate optimal set point values to the BMS in real-time via this software. Additional features were implemented to ensure a reliable operation of the entire

software tool chain. These features monitor the status of the applications and in the rare occurrences when it fails the site BMS retakes control of the building HVAC system.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The broad application of building energy management systems that apply advanced methods for HVAC operational controls and energy diagnostics to DoD's facilities is key for achieving the DoD's energy reduction targets. The energy reduction is achieved by providing HVAC set points that would optimize system level performance and applying energy performance monitoring and diagnostics that enable facility engineers to more proactively identify and correct poor system performance. A 40% HVAC system energy reduction achieved through the application of the proposed technologies would offer greater than $150M per year savings potential across all existing DoD facilities with district heating systems[6].

The developed EPMO system differs from existing advanced building energy management systems in the following ways:

- Integrating HVAC equipment set point optimization and fault detection and diagnostics algorithms in a first-of-a-kind system for determining the most efficient set point values when HVAC equipment malfunctions while maintaining thermal comfort whenever possible.
- By employing a set point optimization algorithm, which uses weather forecasts, HVAC equipment models, and zone temperature models for minimizing energy consumption while meeting thermal comfort.
- By employing a model-based approach (for heat exchangers, temperature dynamics, power consumption) to reduce the manual tuning required for most of the currently implemented advanced BMS.

The developed and demonstrated EPMO technology was matured to Technology Readiness Level 6 (TRL) and several aspects need to be further investigated:

- The trade-off between instrumentation cost and the energy consumption levels for various types of buildings is not completely known. The number of sensors installed as part of the demonstration of the EPMO system was small based on the fact that the AHUs in the two demonstration buildings were similar. This resulted in decreased instrumentation cost, but increased the uncertainty in the energy consumption.
- The EPMO technology requires expert assistance and could not be transferred to the site facilities. The EPMO system was demonstrated for several days at a time but there were occasions when the optimization algorithms generated warnings that could only be analyzed by an expert. The complete list of warnings is not completely known for all the scenarios (weather, load, equipment health status) that might be encountered. More demonstration data is needed to determine all scenarios that can occur.

[6] Energy savings are based on: 1) 0.06 quads BTU chilled water sent out from district cooling systems in the DoD facility; 2) 1 kW/ton efficiency for chilled water plant; 3) Average 10 cents per kWh.

- The implementation cost was reduced compared to previous demonstrations due to the employment of software tools that automate part of the design. This cost can be further reduced by automating even larger parts of the EPMO system.
- The limits of robustness of the EPMO system have only been partially tested. Due to the complexity of the system, the system was tested during a limited time period when specific faults were injected (by overriding specific HVAC set points as described in other sections). At the completion of the demonstration there is limited data to determine what the performance degradation limits are for various faults.

3.0 PERFORMANCE OBJECTIVES

The EPMO system results are shown in Table 1 and discussed in detail in Section 6.

Table 1. EPMO System Performance.

Performance Objective	Metric	Data Requirements	Success Criteria[7]	Measured Performance
Quantitative Performance Objectives				
Reduce Campus Energy Consumption (Energy) & Greenhouse Gas Emissions (CO_2)	Building total electric consumption (kWh/ft^2-yr), and peak demand (kW) Steam consumption for heating plant operation (thermal/ ft^2-yr) and peak demand Building total equivalent CO_2 emissions (kg)	Metering data for building electric and heating plant steam usage Building simulation data for equivalent CO_2 emissions	>20% reduction in building total energy consumption (over baseline) >15% reduction in building peak demand energy (over baseline) >20% reduction in building total equivalent CO_2 emissions (over baseline)	>40% reduction in building total energy consumption (over baseline) >10% reduction in building peak demand energy (over baseline) >40% reduction in building total equivalent CO_2 emissions (over baseline)
Reduce HVAC Equipment Specific Energy Consumption (Energy)	Specific energy consumption for each individual component Steam-to-hot-water heat-transfer plant (BTU/ton) AHU (kW/ton) Fan (kW/CFM) Pump (kW/gpm)	Sub-metering data for all HVAC equipment to compute energy and mass flows through each unit	>10% reduction in HVAC equipment energy consumption (over baseline)	Objective not met: Insufficient meters[8] to estimate specific energy consumption
Reduce Building Loads (Energy)	Lighting loads (kWh) Plug loads (kWh)	Sub-metering data for lighting and plug loads	5-10% reduction in lighting and plug loads (over baseline)	Objective not met: The lighting and plug loads were not addressed in the selected demonstration buildings[9]
Maintain/Improve temperature regulation[10]	Average zonal temperature deviation [°C] (from set points) during periods of occupancy when systems (heating plant, AHUs, VAVs) operate without faults	Zone temperature measurements and set-points during no-fault system operation	Metric with optimized control policy <= Metric with baseline control policy	Discomfort reduced by 75%[11]

[7] Success criteria related to building and HVAC equipment energy consumption were assessed using both model-based simulations and actual energy measurements.
[8] All relevant meters were installed for chillers. When the chillers started to malfunction in 2011, the team changed focus, with approval from ESTCP, to heating plants. However, a significant part of the instrumentation budget was spent on chiller meters.
[9] At the time when these performance metrics were proposed, the team selected different buildings at the Navy campus for which reduction in lighting and plug loads presented a larger potential. In buildings 7113 and 7114 where the demonstrations were conducted, lighting and plug loads are significantly smaller compared with thermal loads.
[10] For system with no faults.
[11] The metric selected for discomfort is the total time when any of the zone temperatures exceeds the comfort band (during heating season this is 68EF-76EF)

Table 1. EPMO system performance (continued).

Performance Objective	Metric	Data Requirements	Success Criteria[12]	Measured Performance
Quantitative Performance Objectives (continued)				
EPMO System Robustness	Percentage of faults classified correctly[13]	Building energy fault identified/classified by EPMO System	85% of faults identified are classified correctly (during the demonstration period)	84% of the faults were classified correctly (during the demonstration period)
EPMO System Payback[14]	Simple payback time, Savings-to-Investment Ratio (SIR), Net Present Value (NPV)	Cost to install and implement EPMO system Savings from using EPMO system	Simple payback time is less than 5 years[15] SIR is greater than 1.25 NPV is greater than 0	Simple payback is 3.56 years SIR = 2.06 NPV = $86,168
Qualitative Performance Objectives				
Ease of Use	Ability of an energy manager and/or facility team skilled in the area of building energy modeling and control to use the technology	Feedback from the energy manager and/or facility team on usability of the technology and time required to learn and use	With some training, an energy manager and/or facility team skilled in HVAC is able to use the EPMO system to identify and correct poor HVAC system performance	Objective not met: EPMO system was matured to TRL in this demonstration. At this level expert, supervision is required.
Prioritization of Energy Faults and Corresponding HVAC System Operation Strategies	Ability to detect, classify and prioritize building faults Ability to prioritize the alternative energy efficient HVAC system operation strategies	Building measured data Building simulation data	Energy manager and/or facility team able to prioritize building faults and corresponding energy-efficient HVAC system operating strategies by comparing simulated or measured building performance for various faults or operating strategies.	Objective partly met: A visualization tool was installed as part of another similar effort. The team did not receive feedback from facilities.

[12] Success criteria related to building and HVAC equipment energy consumption were assessed using both model-based simulations and actual energy measurements.
[13] Faults, which can be verified using functional tests.
[14] This payback success criterion is only applied to the case when the only retrofits considered are those that do not involve major equipment retrofits.
[15] DoD Energy Managers Handbook http://www.wbdg.org/ccb/DOD/DOD4/dodemhb.pdf

4.0 FACILITY/SITE DESCRIPTION

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The selected demonstration campus consisted of Buildings 7113 and 7114 at Naval Training Center, Great Lakes, IL. Building 7113 is a 149,875 ft^2 recruit barracks and is a long rectangular building, consisting of a large block of berthing compartments, heads (bathrooms), laundry rooms, classrooms, a quarterdeck with a two-story atrium and office spaces, and a large cafeteria/galley. Buildings 7113 and 7114 were functionally similar (i.e., include barracks, classroom, and cafeteria etc.) and share common central steam-to-hot-water heat-transfer plant.

4.2 FACILITY/SITE CONDITIONS

When Buildings 7113 and 7114 are occupied by recruits, the buildings are occupied 24 hours a day for 7 days a week. Recruits spend about 85% of their time in the barracks. They leave the barracks for drills and marches and during personal time on Sunday and holidays. The HVAC equipment in Building 7113 is located in five mechanical rooms and attic space. Building 7114 shares the absorption chillers, cooling tower, heating hot water heat exchangers, chilled water pumping system, heating hot water pumping system, and the condenser water pumping system with Building 7113. The HVAC equipment in Building 7114 is located in six mechanical rooms and attic space.

A distributed direct digital control (DDC) control system, APOGEE™ Insight by Siemens Building Technologies is installed in Buildings 7113/7114. This system monitors all major lighting and environmental systems. Building electric and water meters will also be read by the DDC system. Operator workstations provide graphics with real-time status for all DDC input and output connections.

The heat water flow generated steam-to-hot-water heating plant is distributed between the five AHUs of each of the two buildings as follows.

Figure 2 illustrates the screenshot from the site BMS and highlights AHU 1 and 2 from both buildings that were used for demonstration.

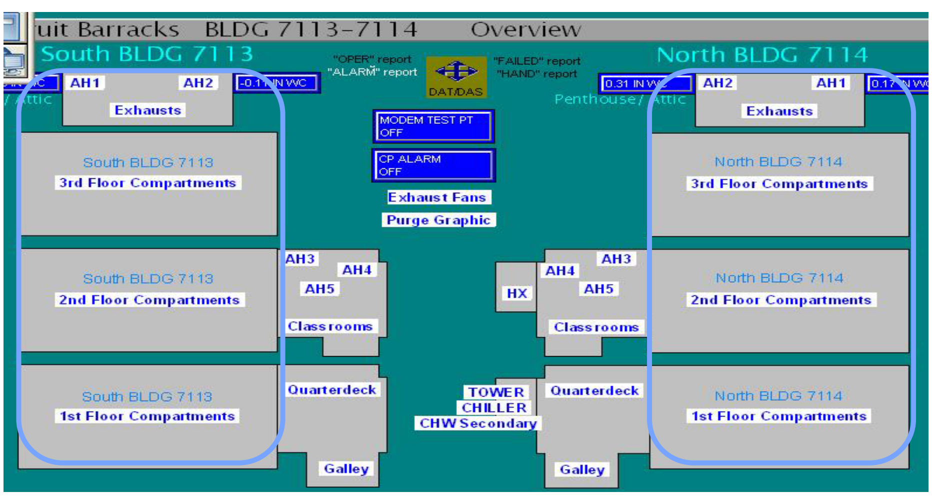

Figure 2. BMS screenshot that shows the AHUs used for demonstration in both buildings.

The EPMO system was implemented for three AHUs serving in total 54 VAV units, therefore controlling about 55% of the two-building site. The three AHUs are: AHU 1 and 2 in Building 7114, and AHU 1 in Building 7113. It was determined that AHU 2 in Building 7114 had some issues with a critical temperature sensor and the project team decided to not include AHU 2 in the demonstration and use it as a baseline for energy performance comparison purposes (for which the temperature was estimated based on other sensor data).

4.3 SITE-RELATED PERMITS AND REGULATIONS

The site specific permits relate to any hot work (i.e., cutting, welding) required for building instrumentation installation (i.e., water flow meters). In addition, electrical Lock-Out-Tag-Out procedures will be used by our subcontractors for installing electrical power instrumentation. No other permits or regulations are applicable other than complying with EM385-1-1 (safety issues) U.S. Army Corps of Engineers, 2008).

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

The project consisted of three demonstrations conducted for several days in November-December 2012 and February-March 2013. The total test duration was approximately 26 days for all three AHUs (two in Building 7114 and one in Building 7113). During the EPMO testing period, the system executed the following tasks:

- Optimal Control: The EPMO system uses real-time data from HVAC, heating plant, and building sensors to determine the optimal set points that could reject the building loads with minimum energy consumption while maintaining occupant comfort.
- Fault Detection and Diagnostics: The EPMO system used BMS real-time data to first detect and then diagnosed HVAC equipment faults. The faults were associated with HVAC actuators (dampers and valves at terminal unit and AHU levels) and were detected based on the discrepancies between model-based predictions and sensor measurements.
- Fault-Accommodation: Upon diagnosing HVAC system faults, the EPMO system adapted the set point values to compensate for the faults while maintaining the occupant thermal comfort with minimum energy possible energy consumption.

The sequential operation of the EPMO technologies and baseline strategies over a heating season 2012-2013 ensures that the performance improvement estimates are consistent and representative for a wider range of operating conditions (i.e., ambient, loads). Baseline strategy is represented by the set point logic implemented in the BMS.

5.2 BASELINE CHARACTERIZATION

The baseline system performance was characterized only for days with the same ambient temperature pattern as the days in which the EPMO system was implemented. The healthy baseline system performance was estimated using the metrics described in Table 1 based on the measurements recorded during normal operation of the HVAC system as explained in Section 6.1. The intent was to use operational data collected during various combinations of load and ambient conditions that could help characterize the variability of the Table 1 metrics.

The faulty baseline system HVAC system performance was estimated using data recorded while the baseline set-point schedule was implemented with controlled faults. The performance estimate of the faulty HVAC system presented challenges due to the randomness inherent in the HVAC component malfunction occurrences. The additional challenge was to replicate the same fault for the EPMO system in order to estimate performance improvements in similar operational conditions. To increase the confidence in the EPMO system improvement estimates, the tests implemented specific faults that were realized by restricting actuator ranges (valves, and dampers) and therefore mimicking the observed and detected naturally-occurring faults. During the demonstration period, these artificial faults were implemented both for the baseline system and for the EPMO system. The characterization of the baseline performance took into account the impact of these malfunctions.

Due to the challenges in replicating similar faults for the baseline and EPMO schedules the baseline characterization had the following limitations:

- Only the impact of *controlled*[16] faults was investigated.
- The controlled fault set was a subset of naturally occurring malfunctions.
- EPMO system performance is subject to large (and only partly known) uncertainty when the load and ambient conditions vary significantly between the baseline and EPMO policy implementation periods.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

Instrumentation and Monitoring Building 7113/7114

The required measurement points and measurement accuracy were taken from the *Specifications Guide for Performance Monitoring Systems* (http://cbs.lbl.gov/performance-monitoring/specifications/).

The additional hardware and software necessary to implement the EPMO system in Buildings 7113 and 7114 are listed in Table 5.1 of the Final Report Approximately 2665 building performance monitoring points were mapped from Siemens BMS to the EPMO system. The cost estimates for these monitoring points are provided in Section 7.

Performance Monitoring System PC Server

The overall system schematic diagram is shown in Figure 3. The PC server that executed the EPMO system was located in the same building location as the PC running the Siemens Energy Management and Control System (EMCS). The Siemens Building Automation and Control Network (BACnet) interface was a gateway between the Siemens server and the EPMO system. The gateway enabled two-way communication of relevant real time building and heating plant measurements between the Siemens server and the EPMO data exchange system through an individual Ethernet connection separated from the Navy's Intranet network.

Within the EPMO system there are several modules necessary to achieve the proposed system functional requirements. The exchange module was transfer the received data to the Data Base module, which will store data into the database. The calibrated reduced order model (ROM) module that represents the design/optimal building performance received the relevant data (e.g., weather data, estimated loads) used by the simulation and execute the reference ROM model at each sampling interval. The ROM simulated results were then passed back to the Data Base module where the results were stored in the database.

The optimal predictive control module used the ROM and sensors measurements to calculate optimal set-points for the district steam-to-hot water heat-exchangers plant. The set-points satisfied the imposed systems constraints and minimize energy cost. The module operated on-line and communicates with the Siemens server through the data exchange and the Data Base

[16] *Artificial* or *controlled* faults: the HVAC test conditions where actuator ranges (valves, fans, dampers) are intentionally restricted, via set point control, to specific and limited operational ranges with the purpose of replicating faults observed during normal HVAC system operation.

module. The optimal performance prediction was also communicated to the Siemens server through the facility manager. The Energy Diagnostic tool communicated directly with the database to retrieve a data history (i.e., building measurements, building reference model predictions and actuator inputs generated by the optimal predictive control). The Energy Diagnostic tool will apply data mining and anomaly detection methods to identify building faults.

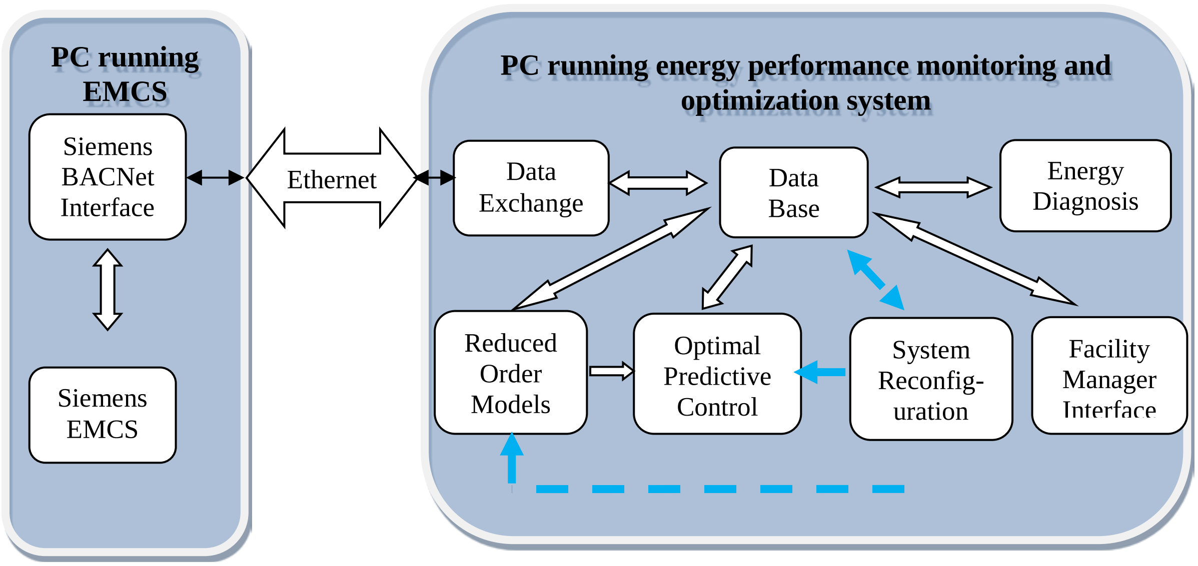

Figure 3. Schematic diagram of the EPMO system main components and its interface with the EMCS.

The database stores all the relevant building performance data, ROM simulation results and the Energy Diagnostic tool results (faults and recommendations) every hour. The database can be any Structured Query Language (SQL) database (e.g., MySQL, PostgreSQL).

The system reconfiguration module was activated when a significant and correctable fault was detected. The module (in conjunction with the ROM and the optimal predictive control modules) was used to predict operational improvements and energy savings that could be achieved when the supervisory control was re-configured to compensate for the fault.

5.4 OPERATIONAL TESTING

The challenge in estimating the performance improvements of the EPMO system stemmed from the randomness of HVAC system faults. Although the staggered schedule operation discussed in Section 6.1 ensured consistency and robustness of performance estimates for healthy systems, the occurrence of different faults while the two systems are operating increases the uncertainty of the performance estimates. To reduce this uncertainty, controlled faults were emulated by means of restricting actuator operational range whenever possible and representative. We distinguished three operational testing scenarios. The characterization of the baseline and estimates of the performance improvements is explained below for each individual test types.

- Test Type 1: In this case, the HVAC system was controlled with both the baseline and EPMO policies, and its operation was not affected by controlled faults. The policy measurements from both experiments were used directly to compute the energy-related metrics described in Table 1 and to estimate the performance of the optimal set point calculation algorithm for a healthy system.

Experiment
Execution

. . . **Baseline Strategy** **EPMO Strategy** . . .

Figure 4. Illustration of testing scenario for the healthy system.

- Test Type 2: In this case, the same controlled faults were injected in the system to test the performance and robustness of the EPMO system. These faults consisted of restrictions to specific ranges of AHU and VAV damper and valve positions. The implementation of these faults was accomplished by constraining the range of mentioned actuators through appropriate set points communicated to EMCS. The same controlled faults were implemented for both strategies and in this case measurements were used directly to estimate energy efficiency improvements. The faults associated with the VAVs, such as constrained ranges for dampers and re-heat coil valves were deemed to have small impact on energy performance. Therefore, they were tested only for a few hours.

Experiment
Execution

Fault
Fault
(same)

. . . **Baseline Strategy** **EPMO Strategy** . . .

Figure 5. Illustration of testing scenario for the faulty system.

The tests described above were implemented as part of the EPMO system demonstration between November 2013 and March 2013 as illustrated in Table 4.3 of the Final Report. In total, the EPMO system was demonstrated for 26 days (all test days combined for all AHUs).

5.5 SAMPLING PROTOCOL

The existing Siemens APOGEE™ EMCS collects all the building performance data, including the additional measurement data proposed by this project. The data communication within the APOGEE™ is accomplished by a Siemens proprietary protocol. In order to acquire the relevant data for this demonstration project, an APOGEE™ BACnet interface was installed. This BACnet interface allowed the existing Siemens EMCS to exchange data with the external data acquisition system through the BACnet protocol. The existing data scan intervals used in the Siemens APOGEE™ EMCS (seconds) were matched by the Data Acquisition module within the EPMO system to ensure the collection of sufficient data to represent the real-world building operating conditions.

BACnet is a communications protocol for building automation and control networks. It is an American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), American National Standards Institute (ANSI), and International Standards Organization (ISO) standard protocol. BACnet was designed to allow communication of building automation and control systems for applications such as HVAC control, lighting control, access control, and fire detection systems and their associated equipment. The BACnet protocol provides mechanisms for computerized building automation devices to exchange information, regardless of the particular building service they perform.

The Data Acquisition module in EPMO system served to acquire the relevant building performance data from the Siemens BACnet interface. The communication was established through an Ethernet connection.

5.6 EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES

Calibration of Equipment

All the equipment components were calibrated by the manufacturer, before the installation was commissioned.

During the building performance monitoring period, sensor data was used to computes various statistics to ensure computed values are within acceptable ranges. Specifically, data for each measured point was used to compute the minimum value, maximum value, mean (average) and standard deviation. These are computed periodically for various lengths of time and the values are compared with reference values obtained from accuracy analysis (using spiked values or duplicates when appropriate). If the computed values were outside of the reference range, then the data is flagged and further analyzed to identify and (and possibly discard) any false data points. All measurement points were directly from existing BMS, the controller vendors (e.g., Siemens at Great Lakes) monitored these points based on control industry standards and protocols to make sure that all the measurements were in the acceptable accuracy band.

Calibration of Reference Model

The ROM model represented the desired performance of the building envelope, HVAC, lighting and control systems. Metering data for building electricity and hot water usage, and sub-metering data for HVAC equipment (e.g., AHUs, heating hot water heat exchangers, pumps) were used to calibrate and validate the ROM model. Real-time weather forecast data was separately entered into the algorithm, due to lack of availability of an Ethernet connection at the site. During the calibration process, some inputs, such as internal gains (loads), were calibrated as accurately as possible.

Quality Assurance Sampling

Data quality was very important for the performance of the EPMO system. The sampling frequency had effects on the types of faults that the system could detect. Higher frequency sampling was limited by the bandwidth capability of the communication network with the BMS. Because the goal was to communicate set points and detect the energy consumption related faults, a five-minute sample frequency was used for most monitoring data. Scripts were used to automatically remove the duplicated data and spiked samples from raw data, synchronize data, and output clean, conditioned data for an analysis within the EPMO system. This process served as a final check before the data is used for diagnostics.

The reality of instrumentation-related research is that missing data is possible even though the instrumentation and monitor systems are designed and commissioned to be reliable. Statistic methods such as extrapolation, interpolation and trend analysis, augmented by domain expertise, were applied to fill the missing data.

Data Analysis

Quality of the data acquired from the BMS was crucial for the success of this project and data quality review was an integral aspect of the proposed approach. Robust data quality evaluation includes testing for precision, accuracy, representativeness (including sampling rate and latency issues) and completeness of the data.

Data precision is the closeness of agreement between indications obtained by replicate measurements on the same or similar objects under specified conditions (Crispieri, 2008). Precision is used to define measurement repeatability and measurement reproducibility. Repeatability is the variability of a measurement due to keeping all controllable and uncontrollable factors constant. It is typically measured by taking data very close together in time, under as close to the same conditions as possible in a laboratory setting. Reproducibility is the variability due to specific controllable or uncontrollable factors by observing measurements at various system configurations. Typical statistical techniques used to accomplish this are analysis of variance and analysis of covariance methods. We use the specification sheets provided by sensor manufacturers as a guideline but in cases where sensors did not perform as expected, further analysis was performed and root causes investigated with the installer's assistance.

6.0 PERFORMANCE ASSESSMENT

The quantitative metric values of Table 1 were estimated based on comparisons between the performance of baseline HVAC control logic implemented in the building BMS and that of the EMPO system. HVAC system performance is affected by several sources of uncertainty that results in large performance variations even for the same control schedule during the same season. These uncertainties impact the EPMO system performance estimates:

- **Leakages:** in supply and return duct; infiltration and exfiltration from the building;
- **Incompletely known baseline control sequences:** it was observed during the EPMO system demonstration that the BMS control sequences were not entirely consistent with the sequence of operations;
- **Equipment health status:** several faults were diagnosed and repaired by the building HVAC technicians for the equipment with more instrumentation; it is possible that several other pieces of equipment were affected by similar faults but these could not be diagnosed due to insufficient instrumentation;
- **Varying thermal loads:** the building is subjected to several load types that cannot be fully determined: occupants, solar radiation, building insulation quality, and open windows.

The performance estimate was based on comparing energy and peak power consumption, and thermal comfort between days when the EPMO system was demonstrated and historical performance of the HVAC system on days with similar ambient temperature.

6.1 QUANTITATIVE PERFORMANCE OBJECTIVES

This section describes in more details the performance metrics calculations summarized in Table 1. The overall results are illustrated in Figure 6 for the following objectives: energy consumption reduction, peak power reduction, discomfort reduction, and fault diagnostics system robustness. Figure 6 also illustrates the overall performance of the EPMO system relative to the baseline HVAC control schedules as averages for all AHUs and all demonstration days. The EPMO system performance for each AHU is illustrated in Figure 7.

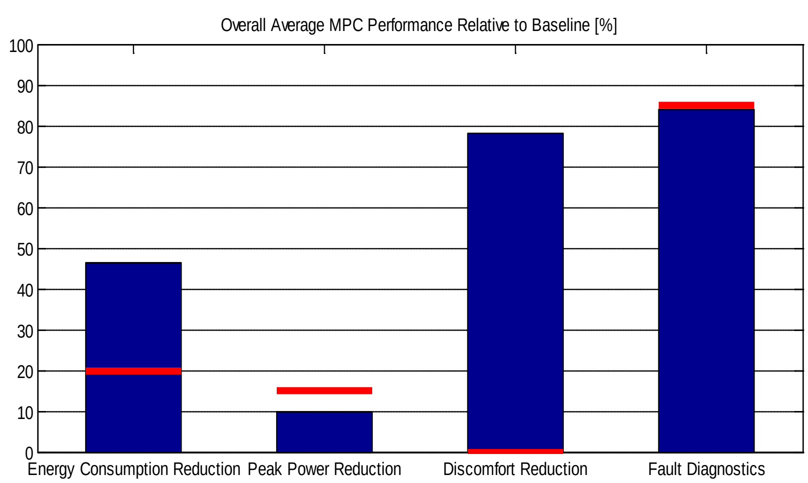

Figure 6. Illustration of overall EPMO system performance relative to baseline schedules.

Figure 7 shows the overall performance as averages across all AHUs and demonstration periods. The targets are illustrated as horizontal red lines.

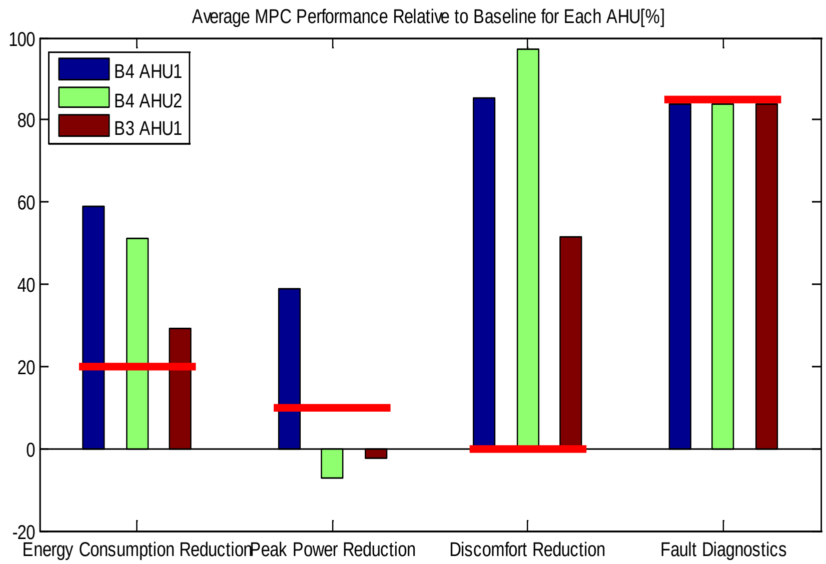

Figure 7. EPMO system performance relative to baseline schedules for each AHU.

The methods and data used to estimate EPMO system performance is detailed below for each quantitative objective.

1. *Reduce Building Energy Consumption (Energy) & Greenhouse Gas Emissions (CO_2).* Results: Quantitative comparisons were done between measured data from the baseline building and the post-commissioning building based on the analytical methodology explained in Section 5.2. As Figure 6 illustrates, the EPMO system reduces energy consumption on average by more than 40% and peak power by 10%. The detailed data for each demonstration period is discussed in Appendix C.2 of the Final Report. Although the peak power was reduced significantly, the 15% target was not achieved. The MPC algorithm generates large peak power levels in particular when the set point changes from unoccupied to occupied periods in order to meet thermal comfort during these transient periods. The MPC-algorithm-generated peaks are larger than those for the baseline algorithm because the BMS schedules do not meet thermal comfort as well as the MPC algorithm does.

2. *Reduce HVAC Equipment Specific Energy Consumption*. The intent was to evaluate the energy consumption reduction at HVAC equipment level for heating plant, pumps, AHU heat exchangers, and fans. Although this component-level metric is less critical than the overall energy consumption of objective #1, it is expected that these measurements could provide more insight into the specific energy trade-offs made by the MPC algorithm. Due to the lack of power sub-metering data and HVAC equipment measurements, these objectives could not be evaluated. The large cost of the instrumentation purchase, installation, and commissioning necessary to calculate all the

equipment specific energy consumption precluded the installation of all the required meters. These costs are relatively large in view of the overall sensor commissioning cost for the EPMO system ($72,580).

3. *Reduce Building Loads (Energy).* The intent was to reduce building loads in order to reduce building demand energy and therefore reduce HVAC system energy consumption. The types of loads that were considered at the beginning of the project were plug and lighting loads. The objective was to reduce these loads during unoccupied times. Two challenges were encountered and could not be overcome: (1) lack of sub-metering data for lighting and plug loads at zone level, and (2) lack of integration of lighting control into the overall site BMS.

4. *Maintain/Improve Temperature Regulation.*
Results: As illustrated in Figure C.3.1 of the Final Report, the MPC algorithm decreased the thermal discomfort by more than 75% relative to the BMS HVAC control schedules.

5. *Energy Performance Monitoring and Optimization System Robustness.*
Results: As Figure C.3.1 of the Final Report illustrates FDD algorithm correctly diagnosed 84% of all events aforementioned, very close to the 85% target. The FDD performance was non uniform across the three AHUs, partially caused by the difference in the instrumentations installed for each AHU.

6. *Energy Performance Monitoring and Optimization System Payback Time.* The overall instrumentation costs are included Table 2 and previously discussed in Section 6.0. The relative energy consumption reduction values are included in Table 3 for each AHU and HVAC subsystem based on demonstration data detailed in Appendix C.2 of the Final Report.

Table 2. Sensor costs (including commissioning) for each HVAC subsystem and EPMO system technology.

System	Calibration/Validation Cost	MPC Demo Sensor Cost	Fault-accommodating MPC Demo
Chiller Plant	0	0	0
Building	13500	0	13600
AHU & VAVs	59350	0	8450
Space	0	0	0
Total	**$72850**	**0**	**$22050**

Table 3. Estimated energy consumption reduction for the main HVAC subsystems and for each AHU.

B7114	B7114A HU1 (kWh)	B7114A HU2 (kWh)	B7114 Total (kWh)	Relative Energy Savings (%)	Absolute Value of Energy Savings (kWh)
Fan energy	47,058	37,793	84,851	6%	5091
Heating coil energy	364,160	438,370	802,530	62%	497,569
Total VAV reheat energy	94,534	32,604	127,138	17%	21,613

Table 3. Estimated energy consumption reduction for the main HVAC subsystems and for each AHU (continued).

B7113	B7113A HU1 (kWh)	B7113A HU2 (kWh)	B7113 Total (kWh)	Relative Energy Savings (%)	Absolute Value of Energy Savings (kWh)
Fan energy	72,682	77,000	149,682	6%	8981
Heating coil energy	519,050	552,980	1,072,030	62%	664,659
Total VAV reheat energy	61,568	49,380	110,948	17%	18,861

Results: The final results, estimated with the NIST BLCC 5.3 software tool, are included in Table 5.1 of the Final Report.

6.2 QUALITATIVE PERFORMANCE OBJECTIVES

1. *Ease of Use.*

   Results: The objective was not achieved. The technology was matured to level TRL 6 but during demonstration the system had to be monitored by experts to ensure it operated robustly. Although the EPMO system can operate automatically for many hours, there might be occasions where the system may slow down for various reasons: loss of communication with BMS, delays in reaching the optimal combination of set points, etc. These reasons, combined with the time constraints caused by the chiller plant malfunctions, led to a TRL level inadequate for non-expert usage. The main focus of this effort was to demonstrate that the EPMO system's benefits make worthwhile further technology development efforts.

2. *Prioritization of Energy Faults and Corresponding HVAC System Operation Strategies.*

   Results: This goal was partially accomplished by re-using the visualization tool developed under the effort in for the project ESTCP EW-201015 for the same building, Building 7114 (Adetola et. Al). This tool was installed at the site and was being executed in parallel with the EPMO system. Although the system operated for a few months, no feedback was received from facility management related its performance and need for improvements.

6.3 DISCUSSION ON THE BENEFITS OF FAULT-ACCOMMODATING CONTROL

A third technology, described in Section 2.2, was demonstrated that integrated MPC and FDD algorithms, referred to in this report as Fault-Accommodating MPC. The demonstration data for this technology was not used to generate the performance metrics of Table 1. The main reason is that the technology was demonstrated for only 2 days, which is considered to be insufficient to generate a realistic indicator of performance. A second reason is that the targets for such a fault-accommodating control system were challenging to be defined, in particular because this was a first-of-a-kind system development and demonstration effort. It is expected that such a fault-accommodating technology will provide a greater synergy of control and diagnostics algorithms because both use similar sensors, models, and computational platforms. It remains challenging however to calculate what the cost benefits are in the absence of quantitative data.

7.0 COST ASSESSMENT

This section details the cost assessment used to estimate the Simple Payback and SIR provided in Table 1.

7.1 COST MODEL AND DRIVERS

The cost model used for the EPMO system cost-benefits analysis is provided in Table 4. This data was entered in the National Institute of Standards and Technology (NIST) Building Life Cycle Cost (BLCC) software tool for estimating the mentioned objectives. The two largest costs are associated with sensor and EPMO system commissioning.

The sensors installed at the site are standard: BTU meters; valve and damper position sensors, and temperature sensors. It should be noted that only one AHU (out of three AHUs used for demonstrations in this effort) and its associated VAVs were instrumented with additional sensors. For the other two AHUs, several models were re-used directly (from the first AHU) with limited validation data. When the systems have similar features in terms of configuration, usage, and size, instrumenting only one component from each category benefits directly the EPMO system. If these AHUs differ significantly in at least one of these features, additional sensors may be required and this leads to larger Payback Time and smaller SIR values than calculated below.

The EPMO system commissioning estimate is based on approximately 2-3 months needed by an expert (the required skills are detailed in Section 8.0) to integrate the models, calibrate, map points, set up the optimization solver components and customize them for the EPMO technology for a specific building.

Table 4. Cost Model EPMO System.

Cost Element	Data Tracked During the Demonstration	Estimated Costs ($)
Instrumentation capital costs plus commissioning cost	Estimates made based on component costs for demonstration; labor and material required to install	$72,850
Software cost	Engineering computational tool, such as MATLAB, and components of the optimization solver	$4000
EPMO system commissioning cost	Estimate based on time required for expert installation	$50,000
Consumables	Estimates based on rate of consumable use during the field demonstration	N/A
Facility operational costs	Reduction in energy required versus baseline data	N/A
Maintenance	Frequency of required maintenance; Labor and material per maintenance action	$2000
Hardware lifetime	Estimate based on components degradation during demonstration	0
Operator training	Estimate of training costs	$2000

7.2 COST ANALYSIS

A simple cost model for drafting technology (DRF)is shown in Table 11 of the Final Report. These represent the actual costs incurred as a part of the demonstration project. The accompanying short notes are included as a footnote.

The overall benefits of the EPMO system were evaluated using the NIST BLCC software tool based on the costs of Table 4 and the energy consumption reduction provided in Table 5.1 of the Final Report. The technology can be applied to the buildings with the following characteristics:

- Medium and large-scale commercial buildings located in geographical areas with similar weather pattern as in Chicago area. Similar HVAC system configuration, e.g. central heating plants serving AHUs that are connected to multiple VAVs.
- The EPMO system can be installed on the same workstation as the BMS. If this is not possible, the costs of the workstation and BACnet gateway, for connecting the new computer with the site BMS, have to be included in the cost-benefit analysis. For example, adding \$3000 to the non-annually recurring costs decreases the Simple Payback to 2.01 and increases the SIR to 3.64. The information from Table 6.2.1 of the Final Report can be used to estimate the investment cost for the EPMO system implementation which is approximately \$0.9/ft^2 for the demonstration buildings. This value is expected to vary for other buildings, depending on the level of existing instrumentation, functionality of the BMS, building insulation, load conditions, etc.
- On-line access to weather forecast data is assumed in the benefit analysis. Due to Internet connection constraints at the Navy site, the forecasts were manually downloaded from the National Oceanographic and Atmospheric Administration website.

8.0

9.0 IMPLEMENTATION ISSUES

This section includes a discussion of the implementation issues in the areas of instrumentation, modeling, BMS integration, network communication, user interfaces and required skills issues.

9.1 INSTRUMENTATION

All instrumentation used in this demonstration is standard commercial off-the-shelf (COTS) products. The recommended measurement accuracies for the power meters and thermal meters are given in *A Specifications Guide for Performance Monitoring Systems* (http://cbs.lbl.gov/performance-monitoring/specifications/). If the BMS is not a 'native' BACnet system, a BACnet gateway will be required to implement the technology. Care is needed when setting up the BACnet gateway. The change of value for updating the measurement for the weather station, power meters and thermal meters should be as small as possible while not overloading the data communication network. Currently, the instrumentation cost is relatively high. The largest components are the equipment and installation costs due to the large number of zones in large commercial buildings.

9.2 MODELING

Matlab was used in this project as the platform for simulation and optimization algorithm execution. For a technology demonstration project, the use of Matlab is appropriate. For broader deployment, existing Matlab code can be compiled and distributed as an executable program. In other words, the EPMO system can be deployed on computers without Matlab.

For some equipment models, including cooling coil, lack of good quality data created some issues for model calibration and validation. Currently, considerable time is spent dealing with issues related to sensor data quality (e.g., sensor bias and drifting) for modeling and diagnostics. Real-time sensor health monitoring provides a means to dramatically reduce the cost related to the commissioning of energy monitoring systems to ensure data quality. Also, information related to building current control sequences was not totally open due to a proprietary BMS on site.

9.3 BMS INTEGRATION

In this demonstration, real time building operational data was collected through a BACnet gateway via a customized middleware software package that enabled applications to programmatically extract data from the system, perform calculations outside of the middleware and finally write data back to the middleware. Examples of such applications are building performance simulation programs, FDD tools, visualization, controls and optimization tools.

9.4 NETWORK COMMUNICATION

Significant challenges were encountered in the development and testing of the advanced building energy management system tool because of remote access problems. Network security constraints prevented the team from having remote access to the computers at Great Lakes. This presented a significant challenge for coding and debugging. Team members could do efficient debugging only while visiting the site. This made it harder for the team to troubleshoot and fix complex and unforeseen issues with the code. It is recommended that remote access be granted for developers implementing similar systems at other sites. This access should be in compliance with DoD information technology policy including Navy Public Service Network. Also, a secured and integrated DoD network should be established for building applications.

9.5 ROBUSTNESS OF OPTIMAL CONTROL TECHNOLOGY

The EPMO system was implemented on three AHUs and during the demonstrations there were several occasions when the solver delayed in reaching optimal set point values for the AHUs and VAVs. The frequency of these occurrences is not yet fully understood. Although at these times the recommended optimal set-point values did not change significantly, there is a need for more demonstration data (during load changes and season transitions) to modify the EPMO system accordingly. These modifications can be in same cases as simple as interrupting the solver when it takes longer than a pre-established duration and re-using the previous set points. These are the simple type of rules that can resolve many of the cases when the algorithm converges slower to the optimal solution.

9.6 REQUIRED SKILLS

The current version of the EPMO system requires the following skills for implementation:

- Creating building and HVAC component models. These models can be standardized for all similar buildings and HVAC subsystems. This project offered direct example of the extent to which these models can be re-used. The models from a project-instrumented AHU were re-used for two other AHUs with less instrumentation.
- Setting up the BACnet gateway and middleware software for bi-directional communication with the BMS.
- Setting up the set-point optimization problem with the HVAC component constraints, energy models, and performance objectives. To a large extent the BLOM tool (Kelman, Vichik, Borrelli, 2013), developed partly with resources from this project, automates the optimal control problem formulation based on expert inputs. Such an environment can be further developed to automate this process to the extent that it requires only standard building and HVAC configuration information.

10.0 REFERENCES

http://cbs.lbl.gov/performance-monitoring/specifications/

http://www.whitehouse.gov/news/releases/2007/20070124-2.html

Adetola, V, S. Ahuja, T. Bailey, B. Dong, T. Khawaha, D. Lou, Z. O'Neil, and M. Shashanka, 2013. *Scalable Deployment of Advanced Building Energy Management System. ESTCP – EW-201015 Project, Technical Report.*

Baotic, M., F. Borrelli, A. Bemporad, and M. Morari, 2008. *Efficient onlin computation...Siam Journal on Control Optimization, 5: 2470-2489, September*.

Borrelli, F. and T. Keviczky, 2008. Distributed LQR Design for Identical Dynamically Decoupled Systems. IEEE Transaction on Automatica Control, 53(8): 1901-1912, September.

Borrelli, F., J. Pekar, M. Baotic, and G. Stewart, 2010. On the Computation of Linear Model Predictive Control Laws. Automatica, 46(6): 1035-1041, June.

DoD Base Structure Report – Fiscal year 2008.

DoD Facilities and Vehicles Energy Use, Strategies and Goals – Program Overview, GovEnergy 2008, August 6, 2008.

G.P. Henze, Kalz, D.E., Liu, S., and Felsmann, C., Experimental Analysis of Model-Based Predictive Optimal Control, *HVAC&R Research*, Vol. 11, No. 2, 2005, pp. 189-213.

M.A. Piette, S. Kinney, and P. Haves. Analysis of an Information Monitoring and Diagnostic System to Improve Building Operations, *Energy and Buildings* 33 (8) (2001), 783-791.

TIAX LLC *Energy Impact of Commercial Buildings Controls and Energy Diagnostics*.. For DOE, May 2005. http://www.epa.gov/cleanenergy/energy-resources/refs.html

http://www.whitehouse.gov/news/releases/2007/01/20070124-2.html

M.E. Brand. Pattern Discovery via Entropy Minimization*. In Uncertainty 99: AISTATS 99,* 1999.

M.E. Brand. Structure Learning in Conditional Probability Models via an Eutropic Prior and Parameter Extinction in *Neural Computation Journal*, Vol. 11,No. 5, pp. 1155-1182, July 1999.

L. Chiang, E. Russell, and R. Braatz, *Fault Detection and Diagnosis in Industrial Systems*, Springer Verlag, London, 2000.

Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, Report of the Defense Science Board Task Force on DoD Energy Strategy, More Fight – Less Fuel, Feb 2008.

Pokrajac, A. Lazarevic, and L.J. Latecki, "Incremental local outlier detection for data streams," *Proc. IEEE Symposium on Computational Intelligence and Data Mining*, 2007, pp. 504-515.

N. Pejcic, N. Reljin, S. McDaniel, D. Pokrajac, and A. Lazarevic, Detection of Moving Objects using Incremental Connectivity Outlier Factor Algorithm, *Proceedings of ACM Southeast Conferenc*e, Clemson, SC, March 19-21, 2009

J. D. Spitler, D.E. Fisher and D.C. Zietlow. 1989. A Primer on the Use of Influence Coefficients in Building Energy Analysis. *Proceedings of the Building Simulation '89 Conference*, pp. 299-304.

Kaplan, M., and P. Canner.1992. *Guideline for Energy Simulation of Commercial Buildings*. Portland: Bonneville Power Administration.

Tuluca, A. 2010. Modeling for Existing Buildings. *ASHRAE Existing Building Conference*. New York, NY.

Keranen, H., Suur-Uski, T. and Vuolle, M. 2007. Calibariton of Building Simulation Model by Using Building Auotmation System- a Case Study. *Proceedings of Clima 2007 WellBeing Indoors*. Helsinki, Finland. June 10-14, 2007

Dudley, J.H., Black, D., Apte, M., Piette, M.A., and Berkeley, P. 2010. Comparison of Demand Response Performacnr with an EnergyPlus Model in a Low Energy Campus Building. *2010 ACEEE Summer Study on Energy Efficiency in Buildings*. Pacific Grove, CA. August 15-20, 2010.

NIST Handbook 135 – *Life Cycle Costing Manual for the Federal Energy Management Program*. 1995.

DOD *Energy Manager's Handbook*.
http://www.wbdg.org/ccb/DOD/DOD4/dodemhb.pdf. August 25, 2005.

U.S. Army Corps of Engineers. *EM385-1-1 Safety and Health Requirements Manual*. September 15, 2008.

T. Bailey, and P. Haves. *ESTCP SI-0929 Automated Continuous Commissioning of Commercial Buildings Demonstration Plan*. February 2010.

ANSI/ASHRAE Standard 140-2007. *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA. 2007.

Crispieri, G. 2008. Data Quality Evaluation Methods. *International SEMATECH Manufacturing Initiative*, Technology Transfer #08074943A-ENG. July 2008.
[Available at http://www.sematech.org/docubase/document/4943aeng.pdf]

N. Bourassa. Automatic Diagnosis for Ailing Rooftop Air Conditioners, *PIER Technical Brief*, July 2005.

R. Radhakrishann, D. Nikovski, K. Peker, and A. Divakaran. Locally Weighted Regression for Fault Detection and Diagnosis of HVAC Equipment, *IEEE Intl. Conf. on Industrial Electronics*, 2006.

A. Lazarevic and Z. O'Neill. United Technology Research Center Real Time Decision Support Project Internal Report. 2008.

M. Giering. "Carrier Building Decision Support Internal Project Report." 2009, 2010.

EPA. Energy Star Building Manual
http://www.energystar.gov/index.cfm?c=business.EPA_BUM_CH3_InvestAnalysis

Ma, Y., Borrelli, F., Hencey, B., Coffey, B., Bengea, S., Packard, A., and Haves, P., "Model Predictive Control for the Operation of Building Cooling Systems", in Proceedings of the American Control Conference, July 2010, Baltimore, MD.

F. Borrelli, and T. Keviczky. "Distributed LQR design for identical dynamically decoupled systems". IEEE Transaction on Automatic Control, 53(8):1901-1912, September 2008.

F. Borrelli, J. Pekar, M. Baotic, and G. Stewart. "On The Computation of Linear Model Predictive Control Laws". Automatica, 46(6):1035-1041, June 2010.

F. Borrelli. "Constrained Optimal Control of Linear and Hybrid Systems", Lecture Notes in Control and Information Sciences, vol. 290. Springer, 2003.

M. Baotic, F. Borrelli, A. Bemporad, and M. Morari. "Efficient on-line computation of constrained optimal control." SIAM Journal on Control and Optimization, 5:2470–2489, September 2008

Lennart Ljung, "System Identification: Theory for the User," Prentice Hall

Roth, K. W., Westphalen, D., Feng, M. Y., Llana, P., and Quartararo, L. (2005). "Energy impact of commercial building controls and performance diagnostics: market characterization, energy impact of building faults and energy savings potential." *Report prepared for U.S. Department of Energy*. TIAX LCC, Cambridge, MA.

S. Sarkar, A. Srivastav, and M. Shashanka, "Maximally Bijective Discretization for Data-driven Modeling of Complex Systems," Proceedings of American Control Conference, (Washington, D.C.), 2013

Kelman, A., Vichik, S., and Borrelli, F., "BLOM: The Berkeley Library for Optimization Modeling and Nonlinear Predictive Control," Internal report, Department of Mechanical Engineering, University of California, Berkeley, 2013. Website: http://www.mpc.berkeley.edu/software/blom

Adetola, V., Ahuja, S., Bailey, T., Dong, B., Khawaja, T., Luo, D., O'Neil, Z., and Shashanka, M., "Scalable Deployment of Advanced Building Energy Management Systems," ESTCP-EW-1015 Project, Technical Report.

http://cbs.lbl.gov/performance-monitoring/specifications/

Narayanan, S., Bengea, S., Lin, Y., Taylor, R., Vrabie, D., Yuan, S., Killough, S., Kuruganti, Manges, W., Woodworth, K., T., Borrelli, F., and Kelman, A., "A Wireless Platform for Energy-Efficient Building Control Retrofits," Final report, ESTCP Project EW-200938, July 2012.

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APPENDIX A

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